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LDRD LW Project Final Report:

Resolving the Earthquake Source Scaling Problem

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February 10, 2003

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This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

LDRD LW Project Final Report: Resolving the Earthquake Source Scaling Problem

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February 2003

One-Year LW Project: October 2002 - September 2003

Tracking Number: 03-LW-004

Executive Summary

The scaling behavior of basic earthquake source parameters such as the energy release per unit area of fault slip, quantitatively measured as the apparent stress, is currently in dispute. There are compelling studies that show apparent stress is constant over a wide range of moments (e.g. Choy and Boatwright, 1995; McGarr, 1999; Ide and Beroza, 2001, Ide et al. 2003). Other equally compelling studies find the apparent stress increases with moment (e.g. Kanamori et al., 1993; Abercrombie, 1995; Mayeda and Walter, 1996; Izutani and Kanamori, 2001; Richardson and Jordan, 2002). The resolution of this issue is complicated by the difficulty of accurately accounting for attenuation, radiation inhomogeneities, bandwidth and determining the seismic energy radiated by earthquakes over a wide range of event sizes in a consistent manner. As one part of our LDRD project we convened a one-day workshop on July 24, 2003 in Livermore to review the current state of knowledge on this topic and discuss possible methods of resolution with many of the world's foremost experts.

In the main part of our LDRD work we have significantly improved upon earlier results by using LLNL developed state-of-the-art techniques over common paths, stations and source regions for earthquake sequences that have a wide range of sizes. We are measuring energy using two independent seismic phases, the direct phase Lg and the scattered coda. We determine energy by integrating spectra from both. Using the 1999 Hector Mine sequence we determine path corrections that match two different teleseismic energy estimates for the Mw 7.1 mainshock. Using these path corrections the aftershocks show decreasing apparent stress with decreasing moment (Mw 3.75 to 7.1). The source spectra follow a Brune (1970) type shape for all events. We can find a different set of path corrections such that the sequence has approximately constant apparent stress, but this results in much larger energy estimates for the mainshock than given by teleseismic techniques and the spectra of the sequence then changes shape with moment. Therefore our initial results indicate that earthquake scaling breaks down, either in the form of variable apparent stress with size, or in the form of variable spectral shape with size.

Introduction and Motivation

Every day there is normally at least one magnitude 5 earthquake somewhere in the world. In fact the smaller the magnitude, the more earthquakes there are in any given time period. This well-known relationship is called the Gutenberg-Richter relation after the scientists who first quantified it. It basically states that the log number of earthquakes of magnitude M , is proportional to that magnitude M plus a constant, with the constant of proportionality for M close to one. This means that there are roughly 10 times more events of magnitude 4 than 5. It also implies that while there are magnitude 2 events on the San Andreas Fault in California every day, the truly great destructive events have repeat times measured in tens to hundreds of years. The last great earthquake (magnitude > 8) on the San Andreas was in 1857, and the last near great earthquake at a magnitude of about 7.75 was the 1906 San Francisco event.

Seismologists have long used the ubiquity of smaller events to help plan and predict what will happen when rare large destructive earthquakes occur. Perhaps the most straightforward way to do this is to take a small earthquake located at the expected site of a future large event and scale up the seismic waves. So for example you might take one or more magnitude 3 earthquakes along the San Andreas Fault in the San Francisco peninsula that were recorded at LLNL and scale them to predict the kind of shaking the lab might undergo in a hypothetical future event. Many papers, studies and maps of hazard have been prepared this way. However there is a fundamental problem with earthquake scaling, scientists still disagree over the correct scaling relationship.

Earthquake scaling is one of the most fundamental unresolved questions in seismology. For example, “Is a magnitude 8 earthquake simply a scaled up magnitude 3 event or do fundamental parameters such as the apparent stress, rupture velocity, and stress drop change with earthquake size?” At first glance it may seem quite surprising that the scaling between large and small earthquakes could be in doubt given the large numbers of earthquakes that occur each year. Much progress has been made in determining the static size of earthquakes in terms of scalar seismic moments using a variety of local, regional and teleseismic techniques. These days it is uncommon to have seismic moment estimates for the same event to differ by more than a factor of two. In contrast, determining the amount of seismic energy radiated in an earthquake, a dynamic measure of size, remains a challenging task and differences much greater than a factor of two for estimates using different techniques are common (*e.g.*, Perez-Campos *et al.*, 2003).

Several factors are responsible for this uncertainty in the amount of energy radiated for each event. First, the majority of seismic energy radiated at the source is in S-waves and concentrated in frequencies within about a factor of about ten of the so-called corner frequency. Energy estimates that do not directly sample S-waves or cannot sample this whole frequency band must make corrections that are subject to sizeable uncertainties. Second, amplitudes at these frequencies are subject to significant path and site effects including geometrical spreading, attenuation and amplification/deamplification due to the surficial layers. Third, the source contains directivity and other inhomogeneities in the radiation pattern that may be difficult to account for and can bias the results if there is

insufficient sampling of the focal sphere to average out these effects (*e.g.*, Favereau and Archuleta, 2003).

The uncertainty in seismic energy leads to different interpretations of the energy density of earthquakes as measured by the Energy/Moment ratio. For many years the prevailing wisdom has been that the energy per moment ratio or apparent stress ($\sim E_R/M_o$) is nearly constant for earthquakes. That is a magnitude 3 and a magnitude 8 have the same apparent stress. However, a number of studies in the past decade or so have found observational evidence that apparent stress increases with moment. In the table below are some papers with observational evidence for increasing scaled energy and some with evidence for constant E_R/M_o .

Table 1. Some papers examining observational evidence for earthquake energy scaling.

E_R/M_o increasing with size (moment)	Constant energy with moment
Kanamori <i>et al.</i> (1993)	Kanamori and Anderson (1975)
Singh and Ordaz (1994)	Choy and Boatwright (1995)
Abercrombie (1995)	McGarr (1999)
Mayeda and Walter (1996)	Ide and Beroza (2001)
Izutani and Kanamori (2001)	Ide <i>et al.</i> (2003)
Prejean and Ellsworth (2001)	
Richardson and Jordan (2002)	

While it is clear that these two interpretations of the existing data are in conflict, the resolution of this issue is complicated by many factors:

- 1) There are large uncertainties in the seismic energy estimates as discussed above.
- 2) Large energy variability for different earthquakes with the same M_o within the same study.
- 3) Lack of common events between studies complicating comparisons of their different results.

Few studies use a single, consistent technique covering a wide range of sizes (*e.g.*, magnitude 3-to-8). Because different techniques can introduce systematic differences in the energy estimates, studies that put a variety of results on one plot risk making “apples-to-oranges” comparisons that may give different results than if a single consistent technique was applied to all the data.

Implications for Earthquake Source Physics

One of the most interesting aspects of an observational constraint on E_R/M_o scaling is the consequence for earthquake source physics. Basically constant E_R/M_o scaling implies similar physics for small and large events. A magnitude 8 is just a magnitude 3 that continued to grow without any change in the physics of the source process. Whereas increasing E_R/M_o scaling with moment implies that large events are more efficient

radiators of seismic energy than small ones, implying that the rupture dynamics of small and large earthquakes differs.

One can imagine a variety of mechanisms that might lead to this behavior. For example, if the dynamic or sliding friction were to decrease as earthquake size increased it could cause this effect. There has been a lot of experimental work studying sliding friction, as well as numerical simulation studies investigating earthquake rupture dynamics looking at the idea of velocity or slip-weakening friction laws. In such laws as sliding begins it causes the friction to decrease leading to further sliding and a sustainable earthquake. It is known that large earthquakes occur with lower than expected driving stress (*e.g.*, Heaton, 1990). Many ideas have been proposed for reducing dynamic friction through some kind of slip weakening process, including shear melting (*e.g.*, Jefferies, 1942; Kanamori and Heaton, 2000), acoustic fluidization (Melosh, 1979), rough fault sliding induced normal stress reduction (*e.g.*, Brune *et al.*, 1993), fluid pressurization (*e.g.*, Sibson, 1973) and elastohydrodynamic lubrication (Brodsky and Kanamori, 2001). Observational constraints on energy release per moment would help us understand and distinguish between these models.

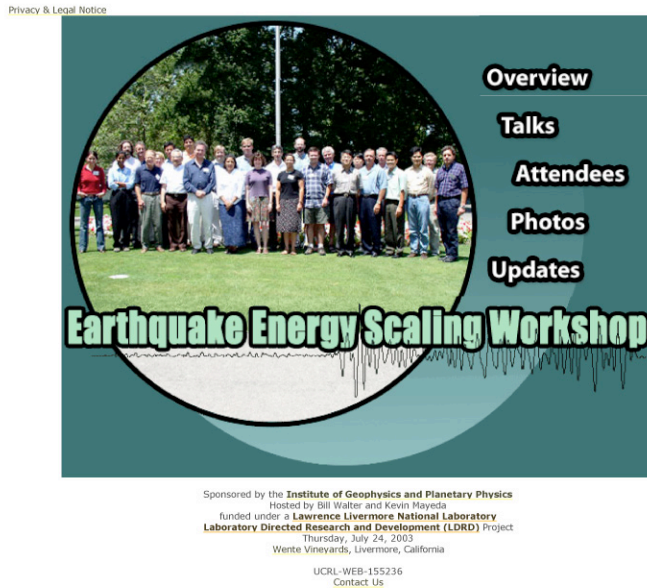
There are alternative views to the ideas of velocity-weakening models explaining observations of increasing apparent stress. For example, in a recent paper by Beeler *et al.*, (2003) they argue that observed changes in apparent stress simply track similar changes in stress drop values. They argue that some of the data showing increasing apparent stress is inconsistent with the changes in efficiency predicted by slip-weakening models and is more consistent with stress drop itself changing in parallel with apparent stress. However one issue is that interpretations of stress drop depend on the assumed model (*e.g.*, circular vs. rectangular, full vs. partial stress drop, etc.) in ways that measures of apparent stress do not. Furthermore it somewhat begs the question of what physics is causing stress drop to systematically increase with moment. A recent paper by Kanamori and Rivera (2003) explores similar themes laying out the interrelations between scaled energy, rupture velocity, and stress drop for a simple model. They note that variable rupture velocity implies variable stress drop even if scaled energy were to remain constant. However if scaled energy varies, it creates the possibility of even larger variability in rupture velocity and stress drop. Interestingly, they find that the product of stress drop and rupture velocity cubed should follow the same scaling behavior with moment as the minimum scaled energy. Clearly better observational constraints on scaled energy variation with moment would help us winnow the large number of possible models of earthquake source physics.

Earthquake Energy Scaling Workshop

As one part of our LDRD project we convened a one-day workshop on July 24, 2003 of some of the world's leading seismic researchers to review the current state of knowledge of seismic energy estimation and earthquake scaling. We had 30 attendees from 12 different institutions in Japan, Israel and the United States. We solicited 15 short presentations with time for questions and discussion. Most of the attendees generously

provided their slides in electronic format. We wrote up a summary of the workshop and created a permanent web site to serve as reference for future work on this topic, as shown in Figure 1.

Workshop Web Site



If forced to chose, do you believe that the available evidence shows:

- 1) Earthquake E_s/M_o scaling is generally constant or increasing over M_w 1 to 8?
- 2) Is your confidence level high, medium or low?

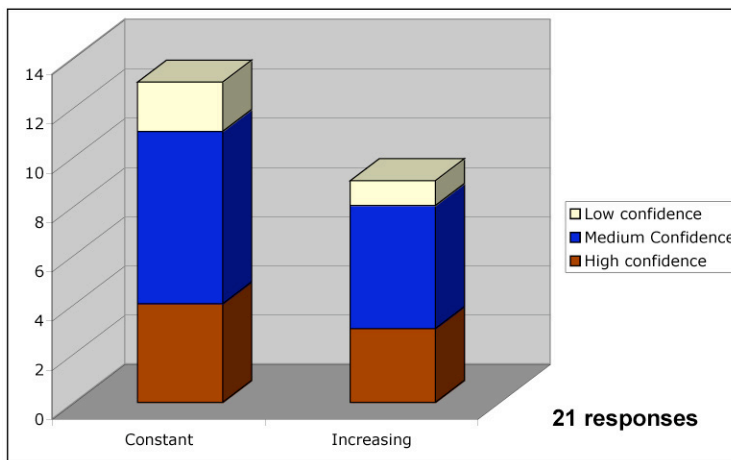


Figure 1. We hosted a one-day workshop on July 24, 2003, and created a web site to document the results and serve as a reference for further research (top). As part of the workshop we asked participants their opinion on earthquake energy scaling, illustrating the geophysical community remains strongly divided on this topic (bottom). See: <http://earthscience.llnl.gov/scaling-workshop/>.

There was very positive feedback on the value of the workshop from the participants. While one day is not sufficient to resolve all the areas of contention regarding earthquake scaling, the workshop nicely framed the debate by reviewing the available data and models and stimulating dialog between competing research groups. At the end of the day someone asked if anyone wanted to change their vote in the straw poll on scaling, to which another participant said “No, but I would lower my confidence level.” This exchange sums up where things stand. We have a number of observational disagreements on energy scaling but the resolution of those differences is not straightforward. More time and effort will be needed to resolve these issues. Towards that end, there are plans for a larger and broader meeting on this topic, an American Geophysical Union Chapman Conference in 2005. We also believe our technical results in the LDRD project provide some new constraints on resolving this issue as described below.

Technical Approach and Analysis

Most prior studies of scaled energy contain many varying parameters such as site effects, path effects, radiation pattern corrections, etc. that produce large scatter and much uncertainty in their determinations of scaled energy. Even when great care is taken to account for these effects different researchers end up with different results. Take for example the 1999 Hector Mine earthquake in southern California. Boatwright *et al.*, (2002) estimate E_R of about 3.3×10^{15} J, whereas Venkataraman *et al.*, (2002) recently revised their initial estimate for this event downward (pers. comm.) to about 1.0×10^{15} J after correcting for finite fault effects. Thus there are baseline differences between researchers working on the same event, since there is no known energy reference event to calibrate to. All of these sources of uncertainty feed into compilation studies of scaled energy such as Ide and Beroza (2001). The resulting large scatter makes it impossible to determine apparent stress scaling or lack thereof.

We believed there was a better way to investigate radiated energy or apparent stress scaling. In our LDRD project we analyzed several major earthquake sequences with a set of consistent local-to-regional distance techniques. We minimize source-path tradeoffs by using common stations and paths for each sequence. We measure the slope of the radiated energy versus moment for each sequence. This minimizes baseline issues, as we expect any such systematic effects apply to all the events of a sequence with less effect on the measured slope. In addition, we estimated uncertainty bounds both on moment and energy. For this purpose we use two independent techniques, to estimate energy, one using direct phase measurements involving Pg and Lg and the other using regional Coda. Comparing these two techniques for each event provides a check on our uncertainty measure and on overall baseline issues. Finally, by using consistent techniques on multiple sequences we can compare them and see if scaling behavior found in each provides a consistent overall picture of if it varies with mechanism and tectonic setting. In summary, our techniques consists of:

- 1) Common stations and paths for earthquake sequences spanning over 4 orders in M_w
- 2) Determination of energy and moment estimates with uncertainties for each
- 3) Measure slope of E_R versus M_o within each sequence
- 4) Use two different self-consistent techniques on multiple sequences and compare results

We chose several major earthquake sequences for which regional broadband data was available and which cover a variety of tectonic settings and geologic environments.

Energy Scaling using the Direct Phase L_g

Here we illustrate how we use the direct regional phases such as L_g to determine radiated energy for events in a large earthquake sequence. The 1999 Hector Mine earthquake sequence in southern California was well recorded on a number of digital broadband stations in the western U.S including ISA, CMB, ELK and TUC. In Figure 2 we show regional direct phase spectra recorded at station ELK for the $M_w=7.1$ mainshock and $M_w=5.3$ and $M_w=4.1$ aftershocks. These are 3 component spectra, averaged over the vertical, east and west components and they are truncated for frequencies where the signal-to-noise ratio drops below a value of two. We note the common path and station indicate that energy differences observed between the phases can be ascribed to source effects.

Also shown in Figure 2 are model fits to the spectra based on the Magnitude and Distance Amplitude Correction (MDAC) regional spectral model of Walter and Taylor (2001). The technique was originally developed to remove such trends from regional earthquake measurements for other purposes. MDAC is based on a generalized Brune (1970) spectral shape that has been altered to allow variable apparent stress scaling. We used an independent estimate of the Hector Mine mainshock moment of $M_w=7.13$ from Ji *et al.*, (2002), and an average apparent stress to do a grid search for the best fitting frequency-dependent apparent Q for each of the phases as indicated in Figure 2. These Q values are then used for all subsequent fitting at that station. The MDAC model spectra in Figure 2 have been generated using an apparent stress that changes with moment and surprisingly, the fits to the aftershock spectra have lower apparent stress than the mainshock.

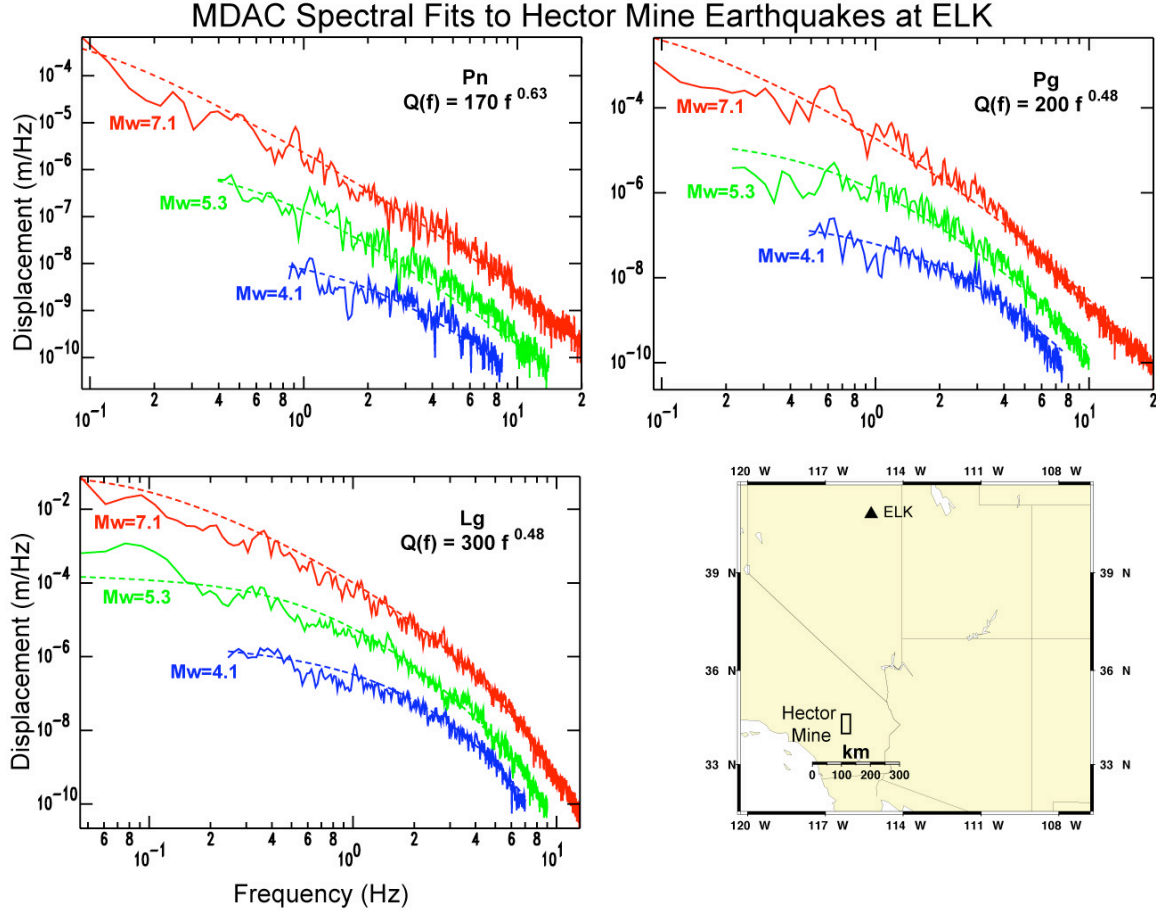


Figure 2. An illustration of regional direct phase spectra and MDAC model fits for the 1999 $M_w = 7.1$ Hector Mine earthquake in southern California and two smaller aftershocks recorded at station ELK in Nevada, about 690 km distant. The spectra are 3-component averages and are cut to where the signal to noise ratio is approximately 2. Spectra for three regional phases Pn, Pg and Lg are shown. The apparent attenuation terms are determined from independent moment and apparent stress values for the mainshock and applied to the aftershocks. The model fits shown here use decreasing apparent stress with moment. The map on the lower right shows the location of the station and the aftershock sequence.

After fixing the path parameters based on the mainshock we perform a grid search over radiated energy with MDAC model and moment determined from the coda (discussed in the next section) to search for the radiated energy for each aftershock. Example spectral misfits and the energy misfit curves are shown in Figure 3. The width of the misfit curve provides a quantitative measure of the uncertainty for each station. The MDAC model fits the data well and automatically builds in corrections for missing energy at the low and high frequency values. In theory, the model can estimate energy from even a small bandwidth signal but in practice the uncertainty curve gets very large. Additional measures of uncertainty come from evaluating the energy measure at different stations (*e.g.*, TUC, ISA, CMB) and different phases such as Pg. Based on a careful

analysis of these effects we choose a lower magnitude cutoff of 3.75 for the Hector Mine sequence at these stations and require at least 3 stations to estimate the average energy of each event.

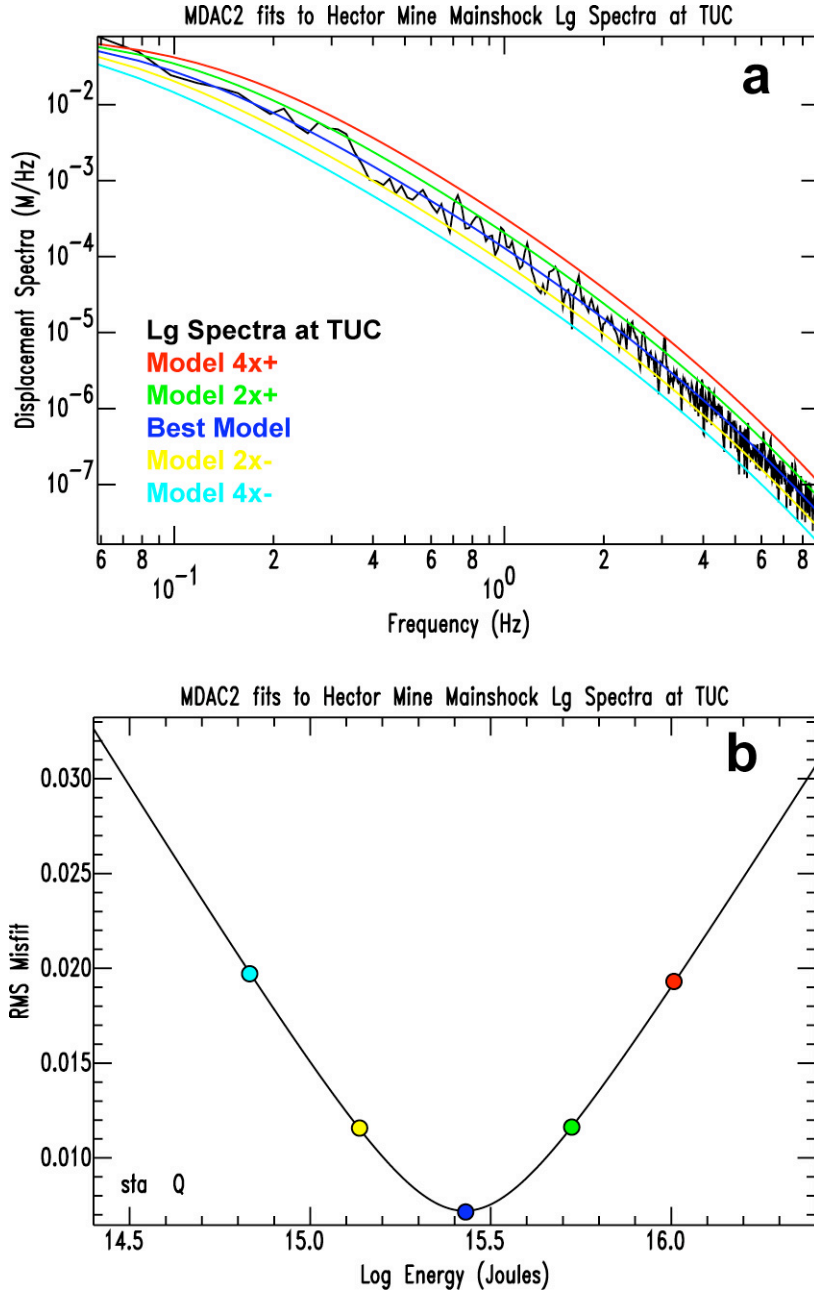


Figure 3. a) The observed spectra at TUC for the 1999 Hector Mine mainshock compared with model fits for a range of radiated energy (or apparent stress) values. The best fit model is shown along with models that have RMS misfits 2 and 4 times larger than the best fit. b) The grid search results showing the misfit versus energy curve. Models shown in (a) are indicated by same color dots in (b).

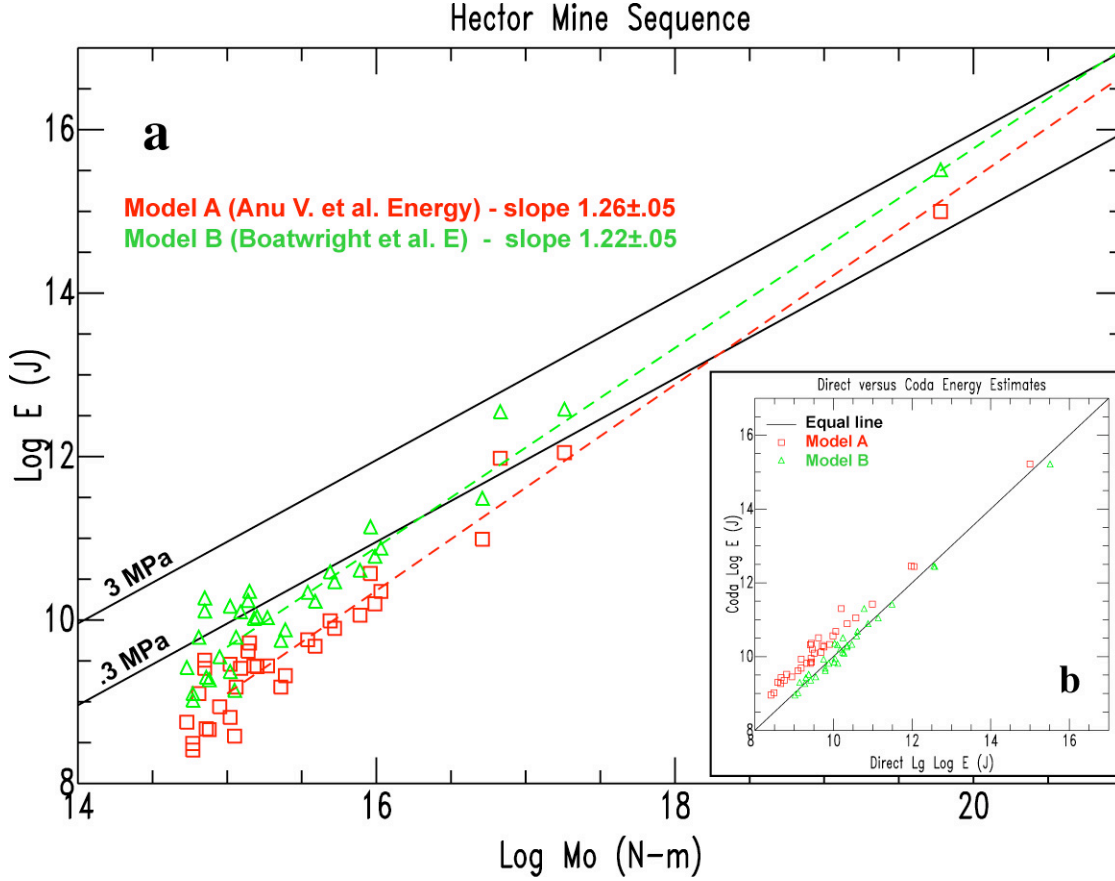


Figure 4. a) Plot of log radiated energy versus log moment for 1999 Hector Mine mainshock and aftershocks greater than M_w 3.75. The energy is based on Lg model fits averaged over at least 3 regional stations from ELK, TUC, ISA, CMB under two different attenuation assumptions. Model A uses a Q determined from the Anu Venkataraman et al. energy, and Model B uses the Boatwright et al. energy for the mainshock as discussed in the text. In either case the data show non-constant apparent stress scaling near the 1.25 slope found in Mayeda and Walter (1996). b) A comparison of the energy determined by the coda technique with that determined by the direct Lg spectra shows a good match with a systematic offset for Model A. (After Walter and Mayeda, in prep.).

We take the average energy for each event and plot it versus the seismic moment in Figure 4 to evaluate the apparent stress scaling behavior. As discussed above, there are (at least) two different estimates of apparent stress for the mainshock. We evaluate the energy scaling for both cases. For Model A we use the Venkataraman et al. revised estimate (pers. comm.) of 1.0×10^{15} J, and for Model B we used the Boatwright et al., (2002) estimate E_R of about 3.3×10^{15} J. For each model we determine the apparent Q for each station by fitting the mainshock. For example, at station TUC Model A gives a $Q(f) = 405f^{0.38}$ and Model B gives a $Q(f) = 260f^{0.52}$ over a range of f of 0.05 to 15 Hz. These

same path Q 's are then applied to all of the aftershocks for each model. The results are shown in Figure 4. We can see that despite a “baseline” difference in absolute energy values, the two different models give similar non-constant scaled energy slopes close to the value of 1.25 observed by Mayeda and Walter (1996). This demonstrates the value of estimating energy scaling within aftershock sequences and shows the diminished dependence of the scaling results on both absolute values of energy and attenuation.

The results shown in Figure 4 strongly support the non-constant apparent stress paradigm. However, in our December 2003 AGU presentation we showed that it is possible to develop path corrections that would lead to a constant apparent stress results, but then the energy estimates are many times larger than those estimated by Boatwright et al. (2003) the largest estimate of which we are aware. Furthermore these corrections would imply that the spectral shape changes so that the largest events no longer resemble a Brune (1970) style spectra. A important focus of our future research in this area is whether such path corrections make sense (e.g. the independent energy estimates are incorrect and spectral shape scaling breaks down), or if as shown in Figure 4 the energy estimates are right and apparent stress scales with earthquake size.

Energy scaling using the Regional Coda

Regional seismic S -wave coda consists of the scattered wavefield following the direct L_g arrival as shown in Figure 5. If the envelopes of the seismic trace are taken in a variety of narrow passbands, estimates of the coda spectra can be derived by fitting the envelopes. By correcting these spectra for path, site, and S -wave-to-coda transfer function effects, a coda-based source spectra can be derived. This regional coda envelope technique for source spectra has evolved over the past decade (Mayeda, 1993; Mayeda and Walter 1996; Mayeda *et al.*, 2003). The most recent version of the methodology has been developed to be completely empirical and independent of assumptions about scattering models. Furthermore, it can be transported to any region and calibrated to the new regional structure (*e.g.*, Phillips *et al.*, 2002, Eken *et al.*, 2003; Morasca *et al.*, 2003, Malagnini *et al.*, 2003). The coda calibration procedure allows an independent check of three important features: (1) that the empirical path corrections provide consistent amplitude measurements for the same event at different stations, distances, and azimuths; (2) that the long-period levels of the coda-derived source spectra are consistent with independent moments from long-period waveform modeling; (3) that small event spectra are flat below a conservative estimate of the corner frequency and thereby effectively accounting for near-site attenuation at high frequencies.

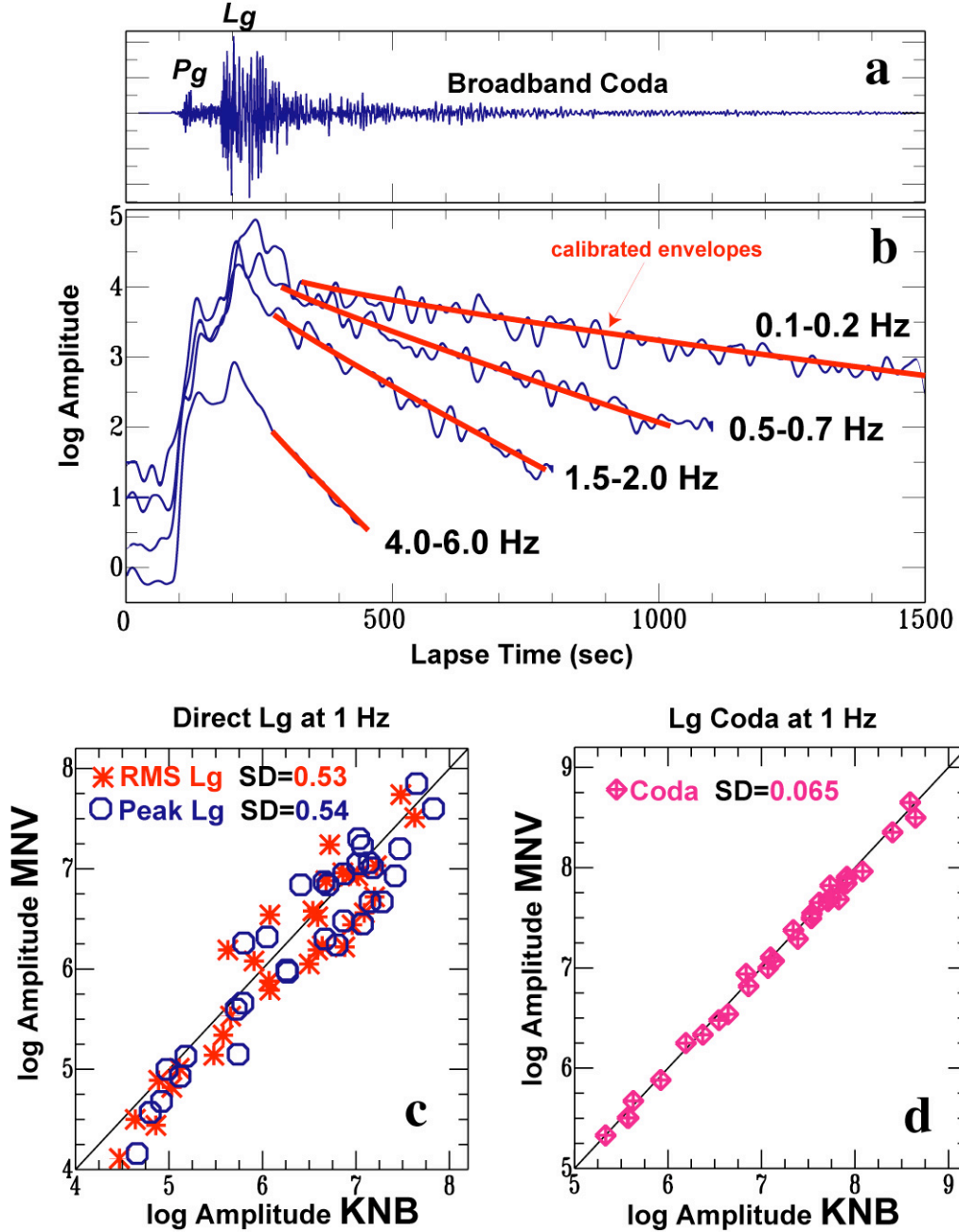


Figure 5. (a) Shows an example regional seismogram where coda is the scattered late arriving energy after the direct Lg arrival. (b) Shows trace envelopes in different filter passbands. Calibrated coda envelopes are shown in red fit to the data to get amplitude measures in each passband. These measures provide a coda derived spectra from which magnitude and energies can be estimated. (c) Direct Lg amplitudes show significantly more scatter than (c) amplitude measures based on coda envelopes. This example is from the western U.S. (Mayeda and Walter, 1996) but the coda methodology has been shown to be transportable and effective in other regions.

We have compared direct waves measures with coda waves (*e.g.*, Mayeda, 1993; Mayeda and Walter, 1996; Mayeda *et al.*, 2003) and find that amplitude measurements of direct waves requires significant multi-station averaging to achieve the same stability as a single coda envelope measurement. Specifically, the stability comes from the fact that: (1) the coda samples a significant part of the focal sphere, in contrast to the direct waves which sample limited take-off angles; (2) the coda envelope amplitude represents a cumulative effect of the entire rupture process, effectively averaging over the source-time function; (3) the scattered wavefield effectively averages over lateral heterogeneities; (4) the simultaneous fit to the observed envelope over a large portion of time minimizes measurement error that effects short-window length direct wave measurements. In general, the studies mentioned previously find that the source amplitude obtained from the coda envelope is a factor of 3-to-4 times more stable than those derived from direct waves. In other words, a single coda envelope measurement is equivalent to a 9-to-16-station average using direct waves. An example of this stability is shown in Figure 5 for events in the western U.S. recorded at two regional stations. With multi-station averaging the direct and coda based measures are in good agreement with each other as shown in the bottom of Figure 4, but the coda based measures have a lower overall variance.

Previously Mayeda and Walter (1996) used the seismic coda to minimize the effects of source radiation pattern, heterogeneous path effects, and near-site attenuation to produce stable estimates of moment-rate spectra, moment magnitude, and radiated seismic energy. They demonstrated that it is possible to produce extremely stable moment-rate spectra for regional earthquakes, even from an observation from a single station. They used bandpass-filtered envelopes from the average of the two horizontal components for consecutive narrow frequency bands ranging between 0.02 and 8.0-Hz, together with a 2-D theoretical multiple-scattering model (Shang and Gao, 1988) in order to produce synthetic coda envelopes as a function of time and epicentral distance. Calibrated synthetic envelopes were used to measure the observed envelope's amplitude as a function of frequency by DC shifting the synthetics until they matched the observed envelopes using an L-1 norm.

In a recent study, Mayeda *et al.*, (2003) improved upon this methodology and adopted a completely empirical approach for the computation of synthetic envelopes and path corrections applicable at both local and regional distances. They argued that scattering theories to-date were still not sufficient to simultaneously predict the local and regional distance scattering using a single formulation. In fact, additional 'ad-hoc' distance corrections had to be used in the Mayeda and Walter (1996) study because the multiple-scattering model was too simplistic. In our LDRD work we used the updated approach of Mayeda *et al.*, (2003). Here we demonstrate its application to the 1999 Hector Mine Sequence as shown in Figure 6. We have calibrated stations ISA, PFO, GSC and TUC for frequency-dependent path and site corrections for $0.02 < f < 8.0$ Hz. The resultant source spectra for selected events are shown in Figure 6a and exhibit very little scatter, despite the wide range in backazimuths. Furthermore, Figures 6a and 6b demonstrate that the seismic moment and energy estimates are extremely stable, with standard deviations well below 0.1. Our preliminary Hector Mine energy estimates follow a

similar trend as those found in the broad area of the western United States (Mayeda and Walter, 1996) and the Cajon Pass borehole study along the San Andreas fault (Abercrombie, 1995).

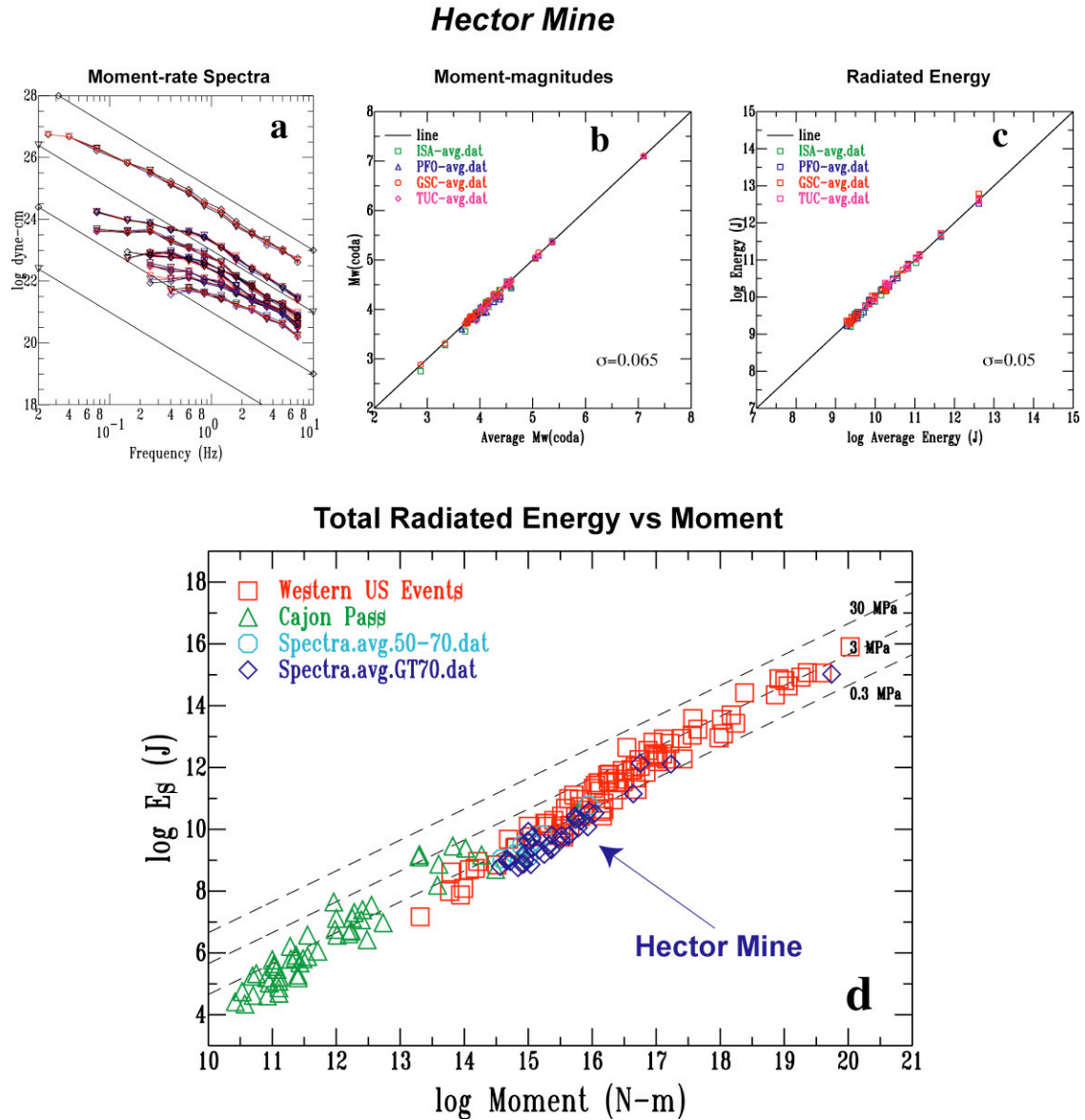


Figure 6. Regional coda envelope technique applied to the 1999 Hector Mine sequence. The top plots show (a) coda derived spectra and (b) the very small inter-station scatter of coda based M_w and (c) energy determinations. The bottom plot (d) shows the coda based log energy versus log moment for Hector Mine events passing 70% (dark blue) and 50% (light blue) energy criteria. The Hector mine events are plotted on top of other western U.S. earthquakes from the study of Mayeda and Walter (1996) and Abercrombie (1995) and show similar non-constant apparent stress scaling, consistent with the direct L_g results in Figure 4.

Conclusions

We believe our LDRD work has significantly improved upon earlier results by using two different consistent techniques over common paths, stations and source regions for earthquake sequences that have a wide range of sizes. Using the 1999 Hector Mine sequence we find both techniques show the aftershocks have decreasing apparent stress with decreasing moment (M_w 3.75 to 7.1). The source spectra follow a similar Brune (1970) type shape for all events. We can find a different set of path corrections such that the sequence has approximately constant apparent stress, but this results in much larger energy estimates for the mainshock than given by teleseismic techniques and the spectra of the sequence then changes shape with moment. Therefore our initial results indicate that earthquake scaling breaks down, either in the form of variable apparent stress with size, or in the form of variable spectral shape with size. We are in the process of refining our calculations and plan to write up our results for publication in a peer reviewed journal.

Accomplishments

Energy Scaling Workshop and Web Site

On July 24, 2003 we convened a one-day workshop in Livermore, California to examine earthquake energy scaling issues. There were 30 attendees from 12 different institutions from Japan, Israel and the United States. We arranged for 15 short invited presentations to be made with significant time for questions and discussion. We were able to compile most of the talks into PDF form, write up a summary of the workshop and put it all together in a public web site which can serve as a reference for future work on this topic. See <http://earthscience.llnl.gov/scaling-workshop/>

Presentations

- Walter, W. R. and K. Mayeda, "Earthquake apparent stress scaling for the 1999 Hector Mine sequence"; Talk presented on December 11, 2003 at the Fall Meeting of the American Geophysical Union, San Francisco, UCRL-JC-155081-ABS.
- Mayeda, K. and W. R. Walter, "Energy scaling for the Hector Mine and Landers sequences"; Talk presented on December 9, 2003 at the Fall Meeting of the American Geophysical Union, San Francisco, UCRL-JC-155206-ABS.
- Walter, W. R., K. Mayeda, R. Gok, J. O'Boyle and S. Ruppert, "Earthquake apparent stress scaling"; Poster presented at the IRIS (Incorporated Research Institutions in Seismology) Annual Workshop, June 19-21, 2003, Fish Camp, CA, UCRL-JC-10196-ABS-REV.

- Mayeda, K. and W. R. Walter, “Earthquake apparent stress scaling”; Talk presented April 10, 2003 at the European Geophysical Society – American Geophysical Union – European Geophysical Union Meeting, Nice France, UCRL-JC-150198-ABS.
- Walter, W. R. and K. Mayeda, “Earthquake apparent stress scaling”; Talk presented December 8, 2002 at the Fall Meeting of the American Geophysical Union Meeting, San Francisco, CA, UCRL-JC-149777-ABS.

Follow-On Work

- Walter, W. R. and K. Mayeda, “Evidence for an earthquake scaling breakdown”; Paper for peer-reviewed journal, in preparation.
- As a follow-up to this LDRD work and using some of the results we have collaborated with Dr. Doug Dreger at U.C. Berkeley to combine our direct and coda methodologies with his finite fault modeling work to examine scaling behavior on some new large earthquake sequences. We wrote and submitted a proposal on this topic to the National Science Foundation for the December 2003 RFP.
- As another follow-up to the LDRD work Dr. Kevin Mayeda is serving on the steering committee for a planned American Geophysical Union Chapman Conference on the topic of Earthquake Energy scaling planned for 2005.

Research Team

Principle Investigator: Dr. William R. Walter is a geophysicist in the Earth Science Division. He is an expert in seismic source modeling and regional propagation. He joined LLNL as a post-doc in 1991 and has worked for many years on the Ground-based Nuclear Explosion Monitoring (GNEM) Program (and its predecessors). He is currently the leader of the GNEM Identification task.

Co-investigators: Dr. Kevin Mayeda is a geophysicist in the Earth Sciences Division. He is an expert in seismic coda analysis and propagation. He joined LLNL as a post-doc in 1992 and has worked for many years on the Ground-based Nuclear Explosion Monitoring (GNEM) Program (and its predecessors). He is currently the leader of the GNEM Yield Estimation task. Dr. Rengin Gok is a post-doctoral seismologist working in the Earth Sciences Division. She is a native of Turkey and brings many years of experience to analyzing earthquakes. Ms. Jennifer O’Boyle is a data specialist and helped assemble the data used in this study. Dr. Stanley Ruppert is a computer Scientist and Geophysicist. He is an expert in large seismic databases, computer networking and infrastructure. He joined LLNL as a postdoc in 1994 and has worked for many years on the Ground-based Nuclear Explosion Monitoring (GNEM) Program (and its predecessors). He is currently the leader of the GNEM Data Management task. Mr. Sean Felker is an undergraduate

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Acknowledgements

We thank IRIS, the USGS, Terrascope and the Berkeley Digital Network for making their seismic data openly available, enabling this study. We thank Rick Ryerson, head of LLNL IGPP Geosciences for arranging the IGPP sponsorship of our Energy Scaling Workshop. We thank Athena Peterson for all of her efforts administering the workshop and for taking the candid photos. We thank Marisa Price for creating the web site design and layout. We thank Greg Beroza of Stanford University for his encouragement in the early stages of planning for this workshop. The workshop was organized and hosted by Bill Walter and Kevin Mayeda under our Lab-wide LDRD funding. This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

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